High- T_c SQUID gradiometer system for magnetocardiography in an unshielded environment

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Abstract

We set up an electronic gradiometer for magnetocardiography (MCG) in an unshielded environment. The electronically balanced gradiometer consists of high-temperature radio-frequency superconducting quantum interference device (rf SQUID) magnetometers. The rf SQUID magnetometers are arranged to form the electronic first-order, four-vector gradiometer, or second-order gradiometer. The output of the MCG signal was filtered by a band pass (1–30 Hz) and power line filters. We can reduce the noise to $\sim 1 \text{ pT Hz}^{-1/2}$ at 1 Hz for second-order or four-vector gradiometers. Two-dimensional MCG imaging is demonstrated. The results are discussed with data measured in the moderate magnetically shielded environment.

1. Introduction

One important application of superconducting quantum interference devices (SQUIDs) is in the field of biomagnetism [1–8]. Biomagnetism refers generally to the measurement of magnetic fields produced by any living organism. These biomagnetic fields range from several tens of picotesla from the human heart down to several hundreds of femtotesla from the human brain. A biomagnetic system is usually set up in a magnetically shielded environment in order to detect small magnetic signals. A biomagnetic system can be quite expensive if a magnetically shielded room is used. In this paper, we report on magnetocardiography (MCG) measurements with electronic gradiometers in an unshielded environment. We found that the magnetic field sensitivity could be reduced to about $1 \text{ pT Hz}^{-1/2}$ at 1 Hz for both the second-order and four-vector gradiometer. The first-order gradiometer shows a slightly higher noise level. We demonstrate MCG signals taken over the chest of a human body.

2. Experiments

Using high- T_c SQUID magnetometers, we set up first-order, four-vector, and second-order electronic gradiometers for MCG systems and we compare the performance in unshielded

and shielded environments. The magnetometers used were high- T_c radio-frequency (rf) SQUID magnetometers (model M900) from the Jülich SQUID Company. The magnetometers show a white noise level of about $300 \text{ fT Hz}^{-1/2}$ while the low-frequency noise at 1 Hz is varied from ~ 0.5 to $1 \text{ pT Hz}^{-1/2}$. Subtraction electronics were built to subtract the environmental noise. The output of the gradiometer is filtered with the notch filter and the low-frequency band pass (1–30 Hz) filter. To increase the signal-to-noise ratio, we averaged the measured MCG signal according to the simultaneously recorded electrocardiography (ECG) signal. For each position we measured the MCG signal for 30 times averaging. The time that the averaging data displayed is chosen to be about the period of a single heartbeat to prevent the loss of any information. Using a computer, we controlled the motion of the X–Y bed and measured the MCG signal over a desired area above the chest of a human body. The X–Y bed can be moved over a scanned area of $50 \times 50 \text{ cm}^2$ for two-dimensional MCG mapping.

3. Results and discussion

3.1. Second-order electronic gradiometer in an unshielded environment

Using the high- T_c SQUID magnetometers, we set up an off-axis electronic second-order gradiometer for MCG in an

Figure 1. Configuration of an off-axis second-order gradiometer.

Figure 2. Configuration of a four-vector gradiometer.

unshielded environment. The magnetometers were mounted in an off-axis arrangement with their sensing planes oriented along the z -axis and separated by the baseline distance of 6 cm. Two reference SQUIDs were mounted at 6 and 12 cm above the sensing SQUID separately, as shown in figure 1. We used subtraction electronics and fast Fourier transform to optimize the environmental noise [9]. Our data show that the 60 Hz spike can be reduced from $40 \text{ nT Hz}^{-1/2}$ to about $1 \text{ pT Hz}^{-1/2}$, i.e. an attenuation factor of about 4×10^4 is achieved in the unshielded environment. The noise level at 10 Hz is $\sim 0.1 \text{ nT Hz}^{-1/2}$ for the magnetometer and it is reduced to $1.5 \text{ pT Hz}^{-1/2}$ for the second-order gradiometer in an unshielded environment.

3.2. Electronic four-vector gradiometer in an unshielded environment

Using three reference SQUIDs, we form the four-vector gradiometer as shown in figure 2. With the difference electronics, we adjusted the parameters to minimize the output $G = Z_1 - \gamma Z_2 - \alpha X - \beta Y$. The distance between the sensing SQUID Z_1 and the reference SQUID Z_2 is about 8 cm. Figure 3 shows the noise spectrum of the electronic four-vector gradiometer measured in optimized parameters and the magnetometers Z_1 , Z_2 , X and Y . The sensing SQUID Z_1 , and the reference SQUID Z_2 , show similar background peaks at 2 Hz because these two sensors are arranged in the same orientation. The difference in the noise spectrum of sensors X and Y is due to the different environmental noise at the reference position in our laboratory. With an optimized adjusting parameter, we can reduce the noise at 1 Hz to

Figure 3. Noise spectrum of the four-vector gradiometer along with the noise spectrum of magnetometers Z_1 , Z_2 , X and Y in an unshielded environment.

Figure 4. Comparison of the noise spectrum for the first-order gradiometer and four-vector gradiometer in an unshielded environment.

$1 \text{ pT Hz}^{-1/2}$ in the unshielded environment in a four-vector gradiometer.

We can form a first-order gradiometer with sensors Z_1 and Z_2 also with the same four-vector configuration. To compare the difference in the noise, we show the magnetic field noise of the first-order gradiometer along with that of four-vector gradiometer in figure 4. The first-order gradiometer shows slightly higher noise level of about $4 \text{ pT Hz}^{-1/2}$ in the low-frequency regime.

We used the four-vector gradiometer to perform the MCG measurements of a healthy person. In figure 5 we show real-time MCG and ECG signals in the unshielded environment obtained from the electronic four-vector gradiometer. An

Figure 5. Real-time MCG and ECG signals measured with a four-vector gradiometer in an unshielded environment.

Figure 6. Two-dimensional mapping of the MCG signal obtained from a four-vector gradiometer in an unshielded environment. The scanned area is $24.5 \times 31.5 \text{ cm}^2$.

averaging of 30 times can achieve a signal-to-noise ratio of 10. Using the X–Y translation bed, we obtained the two-dimensional MCG signal. In figure 6 we show the MCG signal in a scanned area of $24.5 \times 31.5 \text{ cm}^2$. An MCG signal with QRS-complex and T-wave wave can clearly be observed. The upper portion shows a positive R-wave while the lower portion shows a negative R-wave. In figure 7 we show a two-dimensional MCG contour obtained from the time instant the R-wave occurred. The points with the same magnitude of MCG signals were connected to form contours of constant magnetic fields. The MCG signal can be generated from the dipoles around the heart. An inverse problem to identify the sources is interesting and is under the investigation. Assuming that multiple dipoles were distributed around the heart, we derived the location of the dipoles and the time evolution. The results will be presented elsewhere. The contours are useful for the identification of the current arrow maps [10, 11].

3.3. Perspectives and developments

The established electronic gradiometers for MCG systems show a noise level of about $1 \text{ pT Hz}^{-1/2}$ for the second-order

Figure 7. Two-dimensional mapping of the R-wave derived from a four-vector gradiometer.

Figure 8. Evolution of the MCG signal in an unshielded environment for strong and weak MCG signals measured at two different positions with 5, 10, 15, 20, 25 and 30 times averaging.

gradiometer or four-vector gradiometer in a noisy laboratory. However, the noisy environment around the laboratory sometimes caused the SQUID to be unlocked. To overcome this problem, we can install the MCG gradiometer systems inside an rf shielded or moderate magnetically shielded room. We tested the gradiometer systems in the moderate magnetically shielded room to check the improvement in its performance. The shielded room has inner dimensions of length, width and height of $2 \times 3 \times 2 \text{ m}^3$, and it was constructed from two layers of mu-metal (2 mm each) and one layer (1 mm) of aluminium. The shielding factors are 46, 56 and 70 dB at 1, 10 and 100 Hz, respectively, tested in the laboratory side. With this magnetically shielded room, we further reduced the noise level of the four-vector gradiometer system to about $\sim 600 \text{ fT Hz}^{-1/2}$. The performance of the SQUID magnetometers inside the shielded room is stable. Figures 8

Figure 9. Evolution of the MCG signal in a magnetically shielded environment for strong and weak MCG signals measured at two different positions with 5, 10, 15, 20, 25 and 30 times averaging.

and 9 show the evolution of an MCG signal in unshielded and magnetically shielded environments for strong and weak MCG signals measured at two positions above the chest with different averaging times. The averaging times are 5, 10, 15, 20, 25 and 30. In the unshielded environment, we obtained a signal-to-noise ratio of 10 for a strong MCG signal (~ 50 pT) in 30 times averaging while for a weak MCG signal (~ 5 pT) the signal is still difficult to resolve even after 30 times averaging if we do not know the time location of the MCG signal. On the contrary, in the shielded environment an averaging of 10 times can achieve a signal-to-noise ratio of 17 for a strong MCG signal (25 pT). Besides, a weak MCG signal (~ 2 pT) can still be resolved after 20 times averaging. To further improve the magnetic field sensitivity of the MCG systems, we can use dc SQUIDs or rf SQUIDs with higher sensitivity. The electronic MCG gradiometer systems set up inside a moderate shielded room are promising for biomagnetic measurements and are very helpful for the noisy environment in hospitals. A research project with the cooperation of the National Taiwan University Hospital using an electronic MCG system in a magnetically shielded environment is in progress.

For the development of electronic high- T_c SQUID MCG systems, Tavrín *et al* [12] studied an axial high- T_c gradiometer for biomagnetic signals. They were able to detect biomagnetic signals in unshielded environments. Based on the same system concept, Tavrín *et al* further developed [13] an axial second-order gradiometer with improved magnetic field resolution. The compensation technique and electronic MCG systems [14–18] were further developed. Electronic high- T_c gradiometers are promising for biomagnetic applications.

4. Conclusion

We have developed electronic first-order, four-vector, and second-order gradiometers and we have compared the performance in an unshielded environment. The noise of electronic MCG systems was reduced to about $1 \text{ pT Hz}^{-1/2}$ for four-vector, and second-order electronic gradiometers in the low-frequency regime. A moderate magnetically shielded room improves the stability in the performance of the electronic MCG gradiometer systems. Two-dimensional MCG imaging in an unshielded environment was demonstrated.

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